GaSe Parametric Oscillator
Pumped by Powerful Holmium Laser near 3 Microns

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Our research work (contract No. F61775-99-WE041) divides into four several tasks:

Task 1. To grow and fabricate new active elements of Ho-crystal. To get a laser oscillation in Q-switch mode with stable wavelength.
Task 2. To study theoretically ways of obtaining GaSe OPO oscillation taking into account the big enough Fresnel losses and the ways to decrease of its influence.
Task 3. To put into operation the Ho-laser with new active elements (see Task 1) and to obtain generation with one or two stages of amplifier at output energy 50 – 100 mJ.
Task 4. To study experimentally the possibility to get OPO conversion efficiency close to 20%.

Task 1 was to grow and fabricate new active elements of Ho-crystal and to get laser oscillation in Q-switch mode with stable wavelength.

In previous contract we had only one Ho-crystal (4mm in diameter and 55 mm in length) for master-oscillator in Q-switch TEMoo mode on the wavelength 2.92 mkm, but during the work the Ho-crystal of master oscillator had changed his lasing properties, namely had changed spectral line of oscillation: instead of one laser line 2.92 mkm this Ho-crystal operates now on several laser lines. The reason is as we think that long time operation in hard regime had led to appearance of color centers which absorption bands had changed oscillation properties of Ho-crystal.

Later we have got two new Ho-crystals: 4 mm in diameter and 77 mm in length and 5 mm in diameter and 90 mm in length. One of them (4 mm in diameter and 77 mm in length) we use for master-oscillator, another crystal was used as amplifier. Laser radiation of master-oscillator was tested with help of monochrometer MDR-4 (focal length is 300 mm, grating has 150 lines/mm and size 40x40 mm) to observe all possible spectral lines of oscillation in Q-switch mode operation.

We have observed 6 spectral lines oscillating simultaneously: 2.84 mkm (strong), 2.91 mkm (week), 2.93 mkm (strong), 2.95 mkm (week), 2.96 mkm (week). Week lines was more than an order less in intensities then strong lines. Accuracy of measuring was not so good because of rather low spectral resolution of our monochrometer MDR-4. But we may suppose that strong lane 2.93 mkm is almost the same that strong line (in former) 2.92 mkm and has no difference for pump source of optical parametric oscillator on the GaSe crystal.

To avoid simultaneously generating many laser lines we have made a laser dispersive resonator by inserting LiF-prizm (60 degrees at the top). The scheme of this resonator is shown on Fig.1.

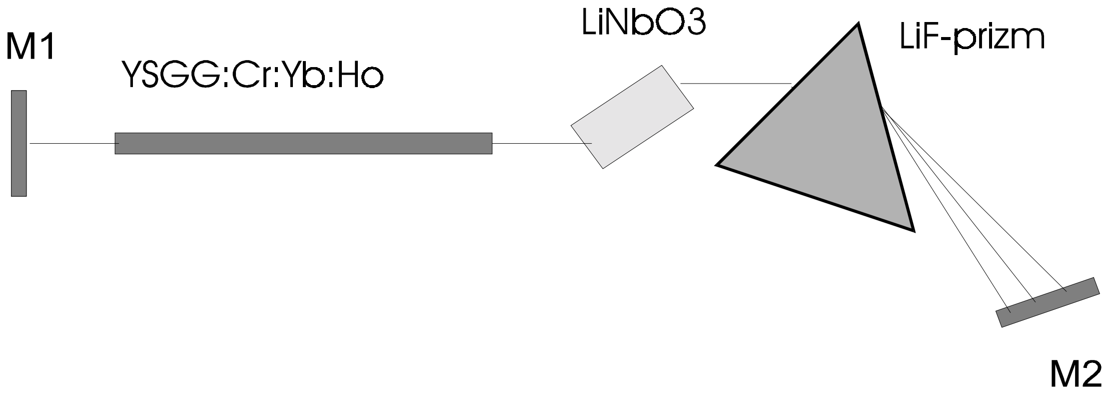


Fig.1. Dispersive resonator for Ho-master-oscillator in Q-switched mode operation.

This laser resonator allow to us to select single spectral lines of laser radiation and we can control this spectral line with help of our monochrometer MDR-4. The proper LiF-prizm adjustment gives single laser line operation with 100% probability.

In our work we select laser spectral line 2.92 mkm. Output energy of master-oscillator in Q-switch TEMoo mode is 10-15 mJ with pulse duration ~150 ns and the gaussian beam diameter 2w~2 mm at the position of Ho-amplifier. About measurements of w see lower.

The holmium crystal-amplifier has diameter 5 mm and the illuminated length of the crystal 80 mm. We have measured output energy of the amplifier vs. amplifier pump energy. The result of our measurements is shown on the Fig.9.

We have so output energy of the single pass amplifier up to almost 60 mJ in Q-switch TEMoo mode operation on the wavelength 2.92 mkm.

<u>The task 2</u> was concerned to study theoretically ways obtaining GaSe OPO oscillations taking into account the big enough Fresnel losses and the ways to decrease of its influence.

We have considered two OPO resonator schemes on GaSe crystals to reduce an influence of Fresnel's losses on threshold power of pumping radiation:

a) one GaSe sample, one of the its sides coated with reflective layer of gold or aluminum; in this case it is redoubled possible length of parametric interaction, but without compensation of birefringence angle for e-waves, Fresnel's losses take place on the input-output GaSe proofs only; increment of amplification of a parametric waves is almost by four times higher (if the losses are rather low) at the same Fresnel's losses (Fig.2).

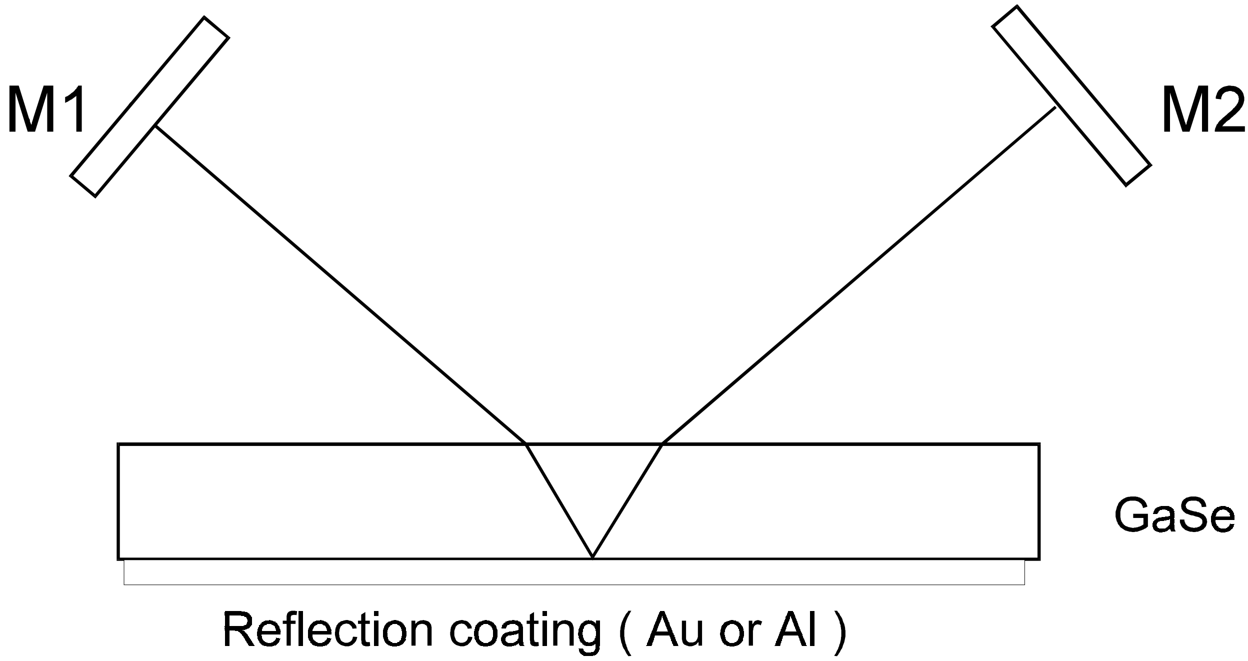


Fig.2

b) two GaSe samples under phase matched angle, but with the compensation of birefringence angle for e-waves (Fig.3). In this case is not required too much radius of gaussian beam of the pumping radiation, but Fresnel's losses are twice more, than for the one sample, but the increment of amplification of a parametric waves is almost by four times higher (if the losses are rather low) at the same Fresnel's losses, as in the case (a).

In fact, if we have one GaSe crystal of the length l inserted between two mirrors and the Fresnel's losses on the both sides of GaSe are δ, then the single path parametric gain is $G(l)= \Gamma^2 l^2 - \delta\cdot l$. In the case (a) we have $G(2l)= (\Gamma\cdot 2l)^2 - \delta\cdot 2l = 4[\Gamma^2 l^2 - (\delta/2)\cdot l]$ and the ratio $G(2l)/G(l)= \{4[\Gamma^2 l^2 - (\delta/2)\cdot l\ ]\}/(\ \Gamma^2 l^2 - \delta\cdot l)\sim 4$ at $\delta\cdot l << \Gamma^2 l^2$. In the case (b) we have $G(2l)= (\Gamma\cdot 2l)^2 - 2(\delta\cdot l) = 4[\Gamma^2 l^2 - (\delta/2)\cdot l\ ]$ and the ratio $G(2l)/G(l)$ is exactly the same as in the case (a) but in the case (b) is there the birefringence angles compensation of two GaSe crystals as it was written above.

The increment of parametric amplification Γ without losses can be written by the next formula (the case of low single path gain and gaussian beams of interacting waves):

$$\Gamma^2 L^2 = (256\pi^2 /c^3)(\omega_s\, \omega_i /n_p n_s n_i)[(d^2_{eff} L^2)/(w^2_p+w^2_s)]P_p ,$$

where P_p is the pumping power, L is the length of parametric interaction,
c - light velocity in the vacuum, n_j - refractive index, w_j - radius of gaussian beam, ω_j - frequencies of interacting waves, d^2_{eff} is the effective quadratic susceptibility, which is equal (for GaSe at different types of interaction) to

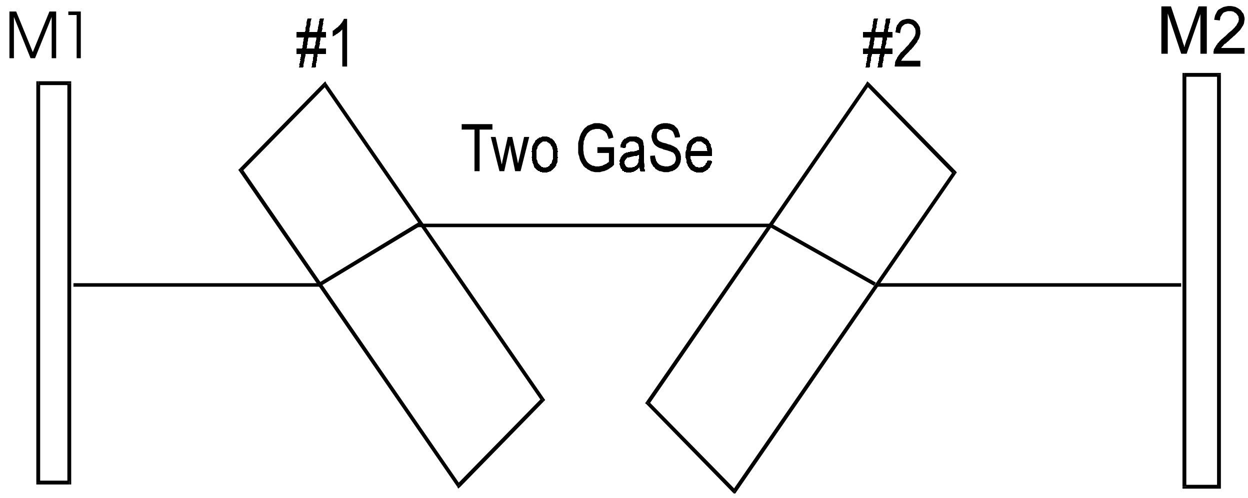


Fig.3

d_{eff} (e-oo) = – $d_{22}\cos\theta\sin3\varphi$ and

d_{eff} (e-eo) = – $d_{22}\cos^2\theta\cos3\varphi$

and where θ is an angle between the wave vector $\mathbf{k_p}$ of pumping radiation and optical axis (lying along the crystallographic axis Z) of the non-linear crystal; φ - an angle between two crystallographic planes (XZ) and ($\mathbf{k_p}$ Z). We need (and can), of course, to choose the angle φ so that sin3φ =1 and cos3φ =1 (must be equal to 1) for e-oo and e-eo types accordingly to maximize d_{eff}.

A calculated tuning curves for GaSe crystal pumped by radiation with λ = 2.92 mkm are shown on the Fig.4a. and Fig.4b. We can estimate $d_{eff}(\theta)$ for both types of interactions from this tuning curves by taking an angle $\theta \sim 11^0$ for type I and $\theta \sim 15^0$ for type II.

The estimations of d_{eff} for this match angles of both types of interactions give:

d_{eff} (e-oo) = – $d_{22}\cos\theta\sin3\varphi$ = – $1.27.10^{-7}$ cm/dyna$^{1/2}$.cos11^0 =

= – $1.25.10^{-7}$ cm/dyna$^{1/2}$

d_{eff} (e-eo) = – $d_{22}\cos^2\theta\cos3\varphi$= – 1.20. 10^{-7} cm/dyna$^{1/2}$.cos$^2 15^0$ =

= –$1.12.10^{-7}$ cm/dyna$^{1/2}$

If we take for simplicity $|d_{eff}|$= $1.2.10^{-7}$ cm/dyna$^{1/2}$ for both types of interactions and take into account the value $n_p n_s n_i$ =17.5 and the values of $w_p = w_s = 0.1$ cm (plan-parallel resonator), we can write the expression for the increment of parametric single path gain Γ:

$\Gamma^2 = (256\pi^2/c^3)(\omega_s\,\omega_i)[(d^2{}_{eff})/(n_p n_s n_i)(w^2{}_p+w^2{}_s)]$ Pp =

= $(256\pi^2/c^3)(\omega_s\,\omega_i)(0.82.10^{-15}$ cm^2/dyna)$P_p/(w^2{}_p+w^2{}_s) = 3.85\mathrm{x}10^{-13}$ [s.cm^{-2}/erg]P_p[erg/s] ,

where $c=3.10^{10}$ cm/s, $\omega_s = \omega_i = 2\pi c/\lambda_{degeneracy} = 5.10^{13}$ s^{-1}, $(\omega_s\,\omega_i)=9.87x10^{28}$ s^{-2} $\sim 10^{29}$ s^{-2} , $(w^2{}_p+w^2{}_s) = 0.02$ cm^2.

If we take output energy after Ho-amplifier $E_{out} = 50$ mJ= 5.10^5 erg, pulse duration $\tau = 1.5.10^{-7}$ s, then $P_p= E_{out}/\tau = 3.33x10^{12}$ erg/s = $3.3x10^5$ W and it gives to us

$\Gamma^2 = 3.85x10^{-13}$ [s.cm^{-2}/erg]P_p[erg/s] = 1.28 cm^{-2} , and then $\Gamma = 1.13$ cm^{-1}.

Now we take into account losses of resonator OPO. The expression for the threshold increment of parametric single path gain Γ_{th} with the losses of resonating parametric "signal" wave Δ_s and not steady-state regime of parametric oscillation with pump-pulse duration τ is:

$\Gamma_{th}{}^2 l^2 = \Delta_s + 60[\,L + l(n\text{–}1)]/c\tau = \Delta_s + \Delta_\tau$,

where L is a total length of OPO-resonator, l is the length of parametric interaction inside of our non-linear crystal (GaSe), n is the refractive index of non-linear crystal, c - light velocity in vacuum, Δ_τ is the non-steady-state part of losses. The "signal" (or the same for "idler") parametric wave losses Δ_s for a good optical quality GaSe crystal are only Fresnel's losses and they could be chosen as the Fresnel' losses of p-component of polarization, which lie in the plane, containing the wave vector **k** of laser radiation and optical axis **C** of the GaSe crystal. In this case $\Delta_s = 4\cdot(\sim 10\%) = 0.4$, i.e. the radiation reflects four times (total path inside a resonator) with ~10% -reflection on each surface of GaSe crystal. The non-steady-state part of losses Δ_τ depends on pump-pulse duration τ (which equals to ~150 ns for Ho-laser) and on L ~10 cm, l ~1 cm, n ~ 2.4 , so that $\Delta_\tau \sim 0.15$. The total loses are $\Delta_s + \Delta_\tau = 0.55$ and at l = 1 cm we have $\Gamma_{th}{}^2 = 0.55$ cm^{-2}.

The estimation of the threshold pump power $P_{p,th}$ gives to us

$P_{p,th}= 0.55$ cm^{-2} /$3.85x10^{-13}$ [s.cm^{-2}/erg] = $1.43x10^{12}$ [erg/s] or $1.43x10^5$ J/s = = 143 kW.

It means that $E_{p,th} = (1.43x10^5$ J/s$)(1.5x10^{-7}$ s$) = 21.5$ mJ .

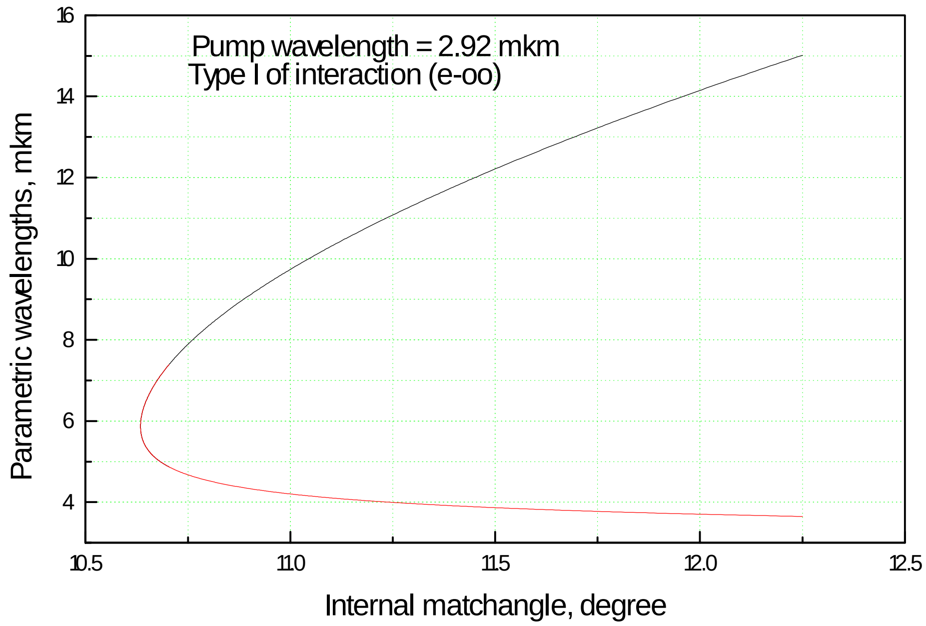


Fig.4a.

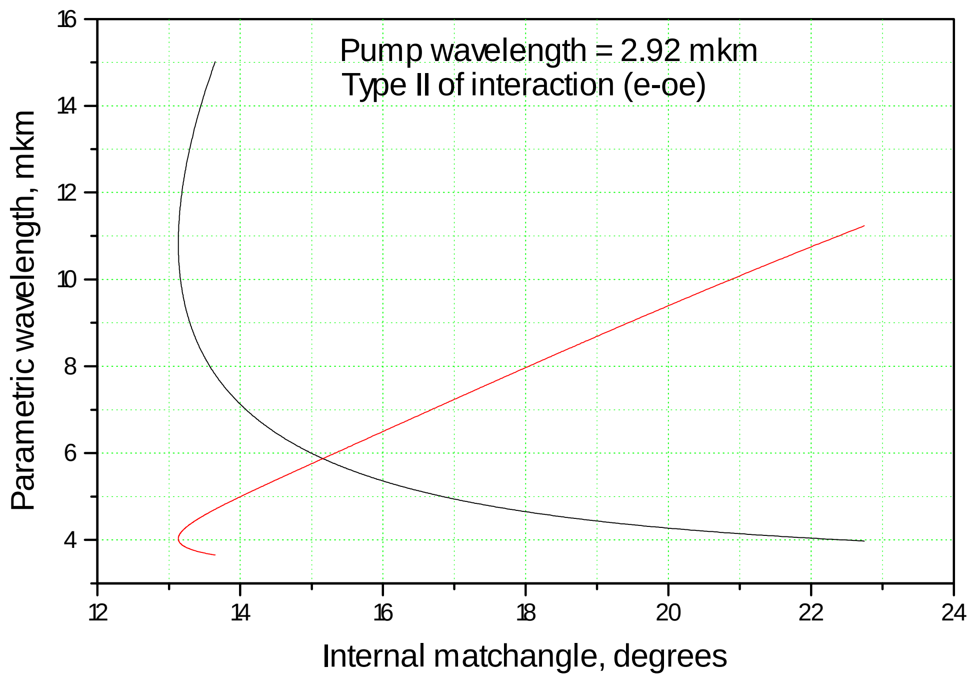


Fig.4b.

If we have $E_{out} = 50$ mJ, then at $l_{GaSe} = 2$ cm (as in the scheme on Fig.3.) we get $\Gamma^2 l^2 = 2.56$ instead of $\Gamma^2 l^2 = 1.28$ if we use only one GaSe crystal.

It should be noted that the energy $E_{out} = 50$ mJ = 5.10^5 erg at the pulse duration $\tau = 150$ ns = $1.5.10^{-7}$ s, gives the pump peak power $P_p = E_{out}/\tau = 3.33.10^{12}$ erg/s, and surface power density P_p/S at the gaussian beam radius w=0.1 cm ($S=\pi w^2/2 = 1.6x10^{-2}$ cm^2) will have the rather high value $P_p/S = 21.2$ MW/cm^2 . This value of P_p/S is very close to damage of the surface of GaSe.

We guess that is the reason of our previous unsuccessful experiments with the operation the resonant GaSe OPO, when we worked with only one GaSe crystal and when almost each laser pump-pulse gave to us the pulse of parametric oscillation, but also gave simultaneously the surface damage of GaSe crystal.

We have made in a metal the scheme like on Fig.3. This scheme is more convenient then scheme on Fig.2. from the point of view adjustment of the OPO resonator. The estimated value above $\Gamma^2 l^2 = 2.56$ is big enough and probably could be decreased but yet having OPO oscillation. We hoped it would be possible the way to get GaSe OPO oscillator without surface damage.

Next part of the final report is concerned to task 3: to put into operation the Ho-laser with new active elements of Ho-crystal and to obtain generation with one or two stages of amplifier at output energy 50 - 100 mJ.

The holmium laser based on the yttrium-scandium-gallium garnet crystal doped with ions Cr^{3+}, Yb^{3+} and Ho^{3+} (YSGG:Cr^{3+}:Yb^{3+}:Ho^{3+}). Concentration of the Ho^{3+} equals to 5.10^{19} cm^3.

The energy levels scheme is shown on the Fig.5.

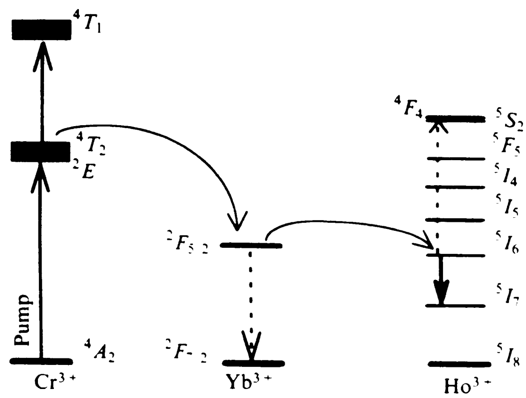


Fig.5.

The laser transition in our case take place between $^5I_6 - {}^5I_7$ energy levels at some wavelengths near 3 mkm in contrary to the case of Ho-laser when it lazing on the wavelength ~2.1 mkm ($^5I_7 - {}^5I_8$). The lifetime of the $^5I_6$ level is equal to 0.47 ms, the lifetime of the $^5I_7$ level is equal to 9.8 ms [1], hence we have self-limited laser transition (and such four-level scheme operate like a tree-level scheme). This energy level scheme shows that pump energy

migrates from the ^2E level of ion Cr^{3+} through the $^2F_{5/2}$ level of Yb^{3+} onto upper laser level $^5I_6$ of Ho^{3+}. Very fast migration gives uniform distribution of the inversion population on the upper laser level in the volume of Ho-crystal.

Two new elements of Ho-crystals were grown and fabricated in GPI, first of them was 4 mm in diameter and 77 mm in length and second one - 5 mm and 95 mm accordingly. The first crystal was used as active element in master-oscillator and the second one was used as active element in one stage amplifier.

When we had a Ho-crystal 55 mm in the length in Q-switched master-oscillator, we observed a single line of generation at λ=2.92 mkm and one very weak satellite at λ=2.84 mkm. The master-oscillator with the Ho-crystal 77 mm in the length gives six lines of generation as in free-running, as in Q-switched regime (obviously, because of length). To select single line of generation we use now a dispersive resonator with 60^O LiF prism. A small-grating monochrometer MDR-4 (100 rules/mm) was used to indicate the lazing wavelength.

We have measured threshold's pump energy E_{th} for each of the six lazing lines. The value of E_{th} depends, of course, on several parameters, on an effectiveness of the illuminating camera, for example. A precision of λ-measurements with help of the monochrometer was small enough, but it was sufficient to separate each lazing line and to determine its wavelength approximately. To measure E_{th} as a function of λ we rotate the LiF prism to move across the spectrum: firstly to increase λ and to measure E_{th} and secondly to decrease λ1 and to measure $E1_{th}$. Experimental data of the lambda-threshold in dispersive resonator with a $LiNbO_3$ crystal as an electro-optic shutter is presented lower.

λ = 2.98 nm	E_{th} = 70.1 J	λ increasing
2.975	58.5	
2.96	46.2	
2.94	51.0	
2.925	40.2	
2.837	40.51	

λ1 = 2.838 nm	$E1_{th}$ = 44.6 J	λ1 decreasing
2.925	44.6	
2.94	51.0	
2.96	48.2	
2.975	63.4	
2.98	73.4	

A graphic dependence of E_{th} and $E1_{th}$ on λ and $\lambda1$ is shown on the Fig.6. We see, that lowest threshold E_{th} take place for two wavelengths 2.84 mkm and 2.92 mkm; the last of the wavelengths is the object of our interest.

So we were working subsequently with the Q-switched dispersive resonator at λ=2.92 mkm.

The length of the resonator was equals to ~ 1 meter, one flat mirror M2 had coefficient of reflection near 100% and output flat mirror M1 had coefficient of reflection 55%; for a Q-switch operation was used electro-optic shutter on the base of $LiNbO_3$ crystal. This experimental set-up is shown on Fig.1.

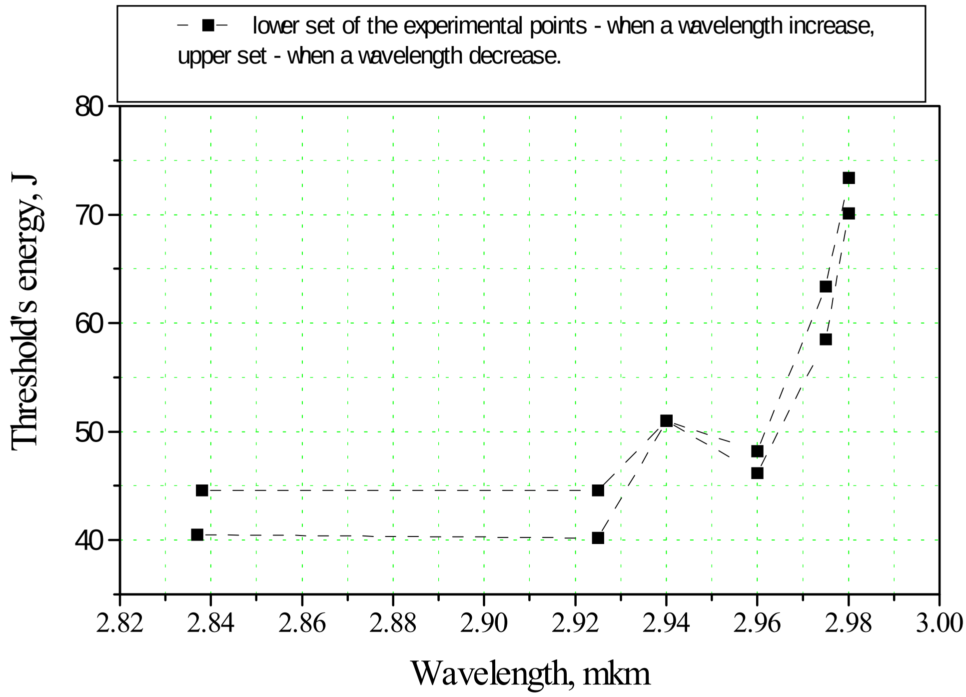


Fig.6.

The output energy of the master-oscillator in Q-switch TEM_{00} -mode at λ=2.92 mkm is about 10-15 mJ with pulse duration ~150 ns and the gaussian beam radius w~1 mm at the position of Ho-amplifier.

We carried out firstly some measurements to determine the output energy of the amplifier E_{out} versus pump energy of them at the constant input energy E_{in} of the amplifier.

A dependence E_{out} on pump energy is shown on Fig.7.

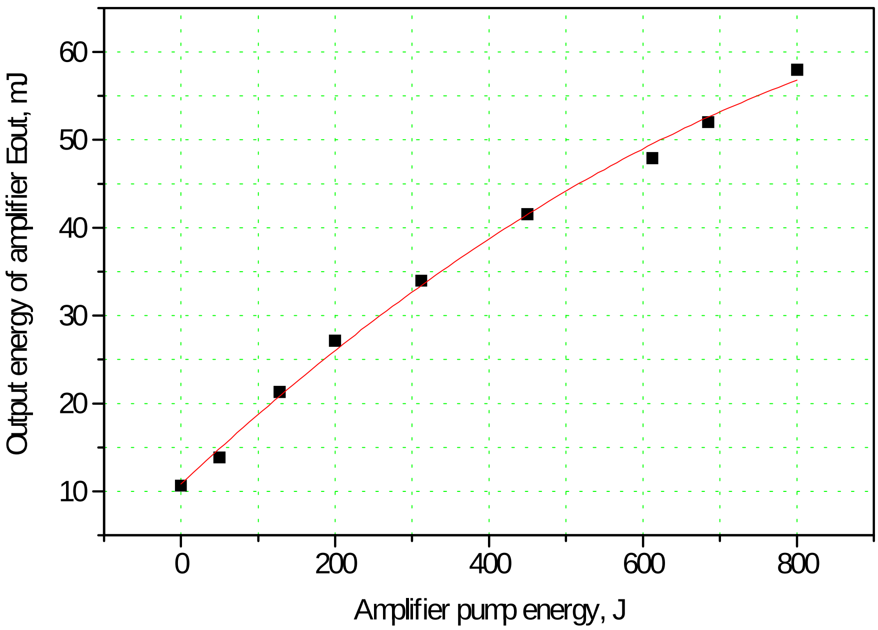


Fig.7.

Crystal-amplifier has 5 mm in diameter, illuminated length of the crystal is 80 mm, input energy of the amplifier is 10 mJ in Q-switch TEM_{00} mode with pulse duration 150 ns and gaussian beam radius w=1 mm.

The pump energy of the amplifier equals to 800 J was the upper limit of the flash lamp, and one stage amplifier gives almost 60 mJ at the input energy equals to 10 mJ, hence G= 5.8 in this case.

It is important to determine some parameters of Ho-amplifier:

1. initial unsaturated coefficient of amplification $\alpha_0[cm^{-1}] = L^{-1} \ln G_0$, which depends on the pumping energy
2. coefficient of non-resonant passive losses $\gamma[cm^{-1}]$
3. energy of saturation $E_s[\,J\,]$
4. extracted energy of amplifier $E_{extr} = E_{out} - E_{in} = \ln(G_0/G)E_s$ and available energy from amplifier $E_{avail} = ((\alpha_0 - \gamma)/\gamma)E_s$, where G_0 and G are unsaturated and saturated gain factors.

As well known (see, for example [2,3]), the laser gain coefficient in a single-pass homogeneously saturated amplifier with unsaturated coefficient α_0 $[cm^{-1}]$ is equal to $\alpha = \alpha_0 \exp[-[\Gamma(t)/\Gamma_s]]$, where $\alpha_0 = \sigma_{eff} N_{20}$, N_{20} is initial inversion population on the upper laser level, σ_{eff} - cross section of the laser transition (in our case – self-limited), $\Gamma(t) = \int_0^t I(t)dt$ is the energy of the giant pulse (with pulse duration t << τ_2 -lifetime of the upper laser level) which

goes into amplifier, $\Gamma_s = h\nu/\sigma_{eff}$ the saturation's energy of four-level scheme with self-limited laser transition.

Note: We have correspondence Γ [J/cm^2] = E[J]/S[cm^2] , where $S=\pi w^2/2$ - laser spot of TEM_{00} – mode of a gaussian beam.

A behavior of current energy density $\Gamma(t,z)$ along the amplifier length (from z=0 to z=L and taking into account non-resonant losses γ [cm^{-1}]) describes next equation:

$$d\Gamma(t,z)/dz = \alpha_0\, \Gamma_s\, (1-\exp(-[\Gamma(t,z)/\, \Gamma_s])) - \gamma\Gamma(t,z)\,, \qquad (*)$$

or by changing $(\Gamma/\Gamma_s) = (E/E_s)$ to F we get

$$dF/dz = \alpha_0\, (1-\exp(-F)) - \gamma F\,.$$

We need to solve this equation (probably - numerically) which describes propagation a short laser pulse in amplifier and to fit properly unknown parameters Γ_s, α_0.

If we could measure unsaturated gain factor $G_0 = (E_{out}/E_{in}) = \exp[(\alpha_0 - \gamma)L]$ at the weak signal E_{in} and measure dependence output energy of amplifier E_{out} on input energy E_{in}, so we could get the value of initial unsaturated coefficient α_0 and then try to solve equation (*) and determine E_s. Usually, in the crystal of good optical quality the main losses are Fresnel's losses, so in the crystal of the length 8 cm with index of refraction n=1.9 we have non-resonant losses $\gamma = 0.027$ cm^{-1}. We have checked experimentally this value and have got a transparency of the crystal-amplifier equals to 80.4% **,** that is in a good agreement with $\gamma = 0.027$ cm^{-1} and L=8 cm.

The next step was to measure dependence output energy of amplifier E_{out} on input energy E_{in} and to try determining basic parameter of our amplifier mentioned above.

On the Fig.8 and Fig.9 are shown result two series of the our measurements at two different pumping energy of the amplifier on the Ho-crystal 9.5 cm of length with the illuminated crystal length of 8 cm.

On the Fig.8 is shown dependence E_{out} on E_{in} at pump energy 300 J.

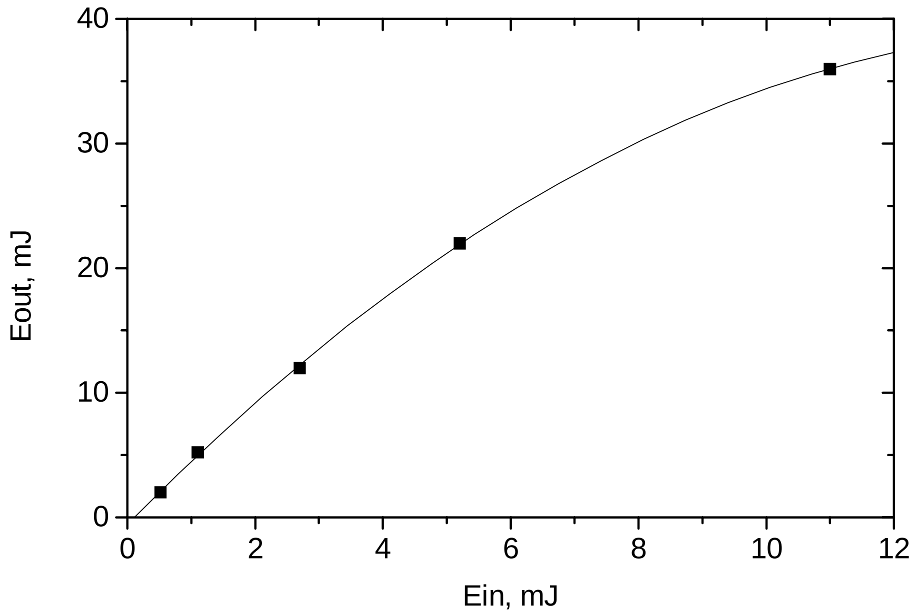


Fig.8.

Polinomial approximation of this dependence gives:

```
Polynomial Regression for Fig.8.
Y = A + B1*X + B2*X^2
Parameter Value     Error
------------------------------------------------------------
A    -0,56455  0,25571
B1   5,20717   0,13421
B2   -0,17109  0,01115
------------------------------------------------------------
R-Square(COD)  SD   N    P
------------------------------------------------------------
0,99981   0,26749   5    1,8754E-4
------------------------------------------------------------
```

where coefficient B1 corresponds to unsaturated gain factor G_0 at the weak input signal 1 mJ< E_{in} < 6 mJ. So we have from Fig.8 the value G_0 = 5.2.

On the Fig.9 is shown dependence E_{out} on E_{in} at pump energy 800 J.

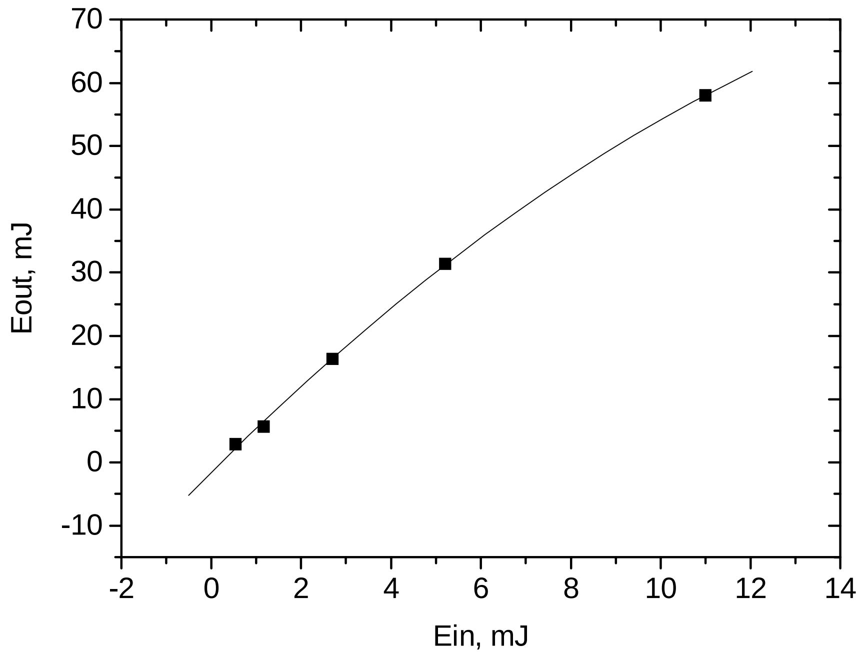


Fig.9.

Polinomial approximation of this dependence gives:

Polynomial Regression for Fig9.

Y = A + B1*X + B2*X^2

Parameter	Value	Error
A	-1,56677	0,75058
B1	7,0839	0,3917
B2	-0,15138	0,03245

R-Square(COD)	SD	N	P
0,99942	0,77062	5	5,8154E-4

where coefficient B1 corresponds to unsaturated gain factor G_0 at the weak input signal 1 mJ< E_{in} < 6 mJ. So we have from Fig.9 the value $G_0 = 7$.

Having experimental data shown above we have to solve numerically differential equation (*) which describes propagation a short laser pulse in amplifier and to fit properly unknown parameters α_0 and E_s (or Γ_s, α_0):

Γ_s – energy density of saturation [J/cm^2],

α_0- initial gain coefficient, cm^{-1},

γ - non-resonant losses, cm^{-1} , which is close to 0.027 cm^{-1} .

We get fit-function (solid line) with help of MATHCAD 6 PLUS program, which is shown on Fig.10. This function approximate our experimental points rather good at values of parameters $\alpha_0 = 0.249$, $\gamma = 0.027$, $\Gamma_s = 0.7$ J/cm^2 . A gaussian beam radius was w=1 mm.

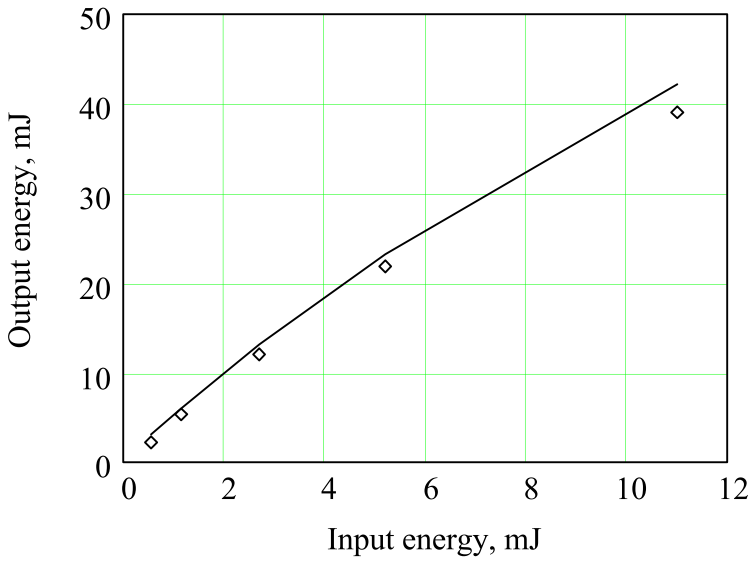


Fig.10.

MATHCAD 6 PLUS gives a curve of a gain factor G in dependence on input energy E_{in} at the same parameters (Fig.11): $\alpha_0 = 0.249$ cm^{-1} , $\gamma = 0.027$ cm^{-1}, $\Gamma_s = 0.7$ J/cm^2.

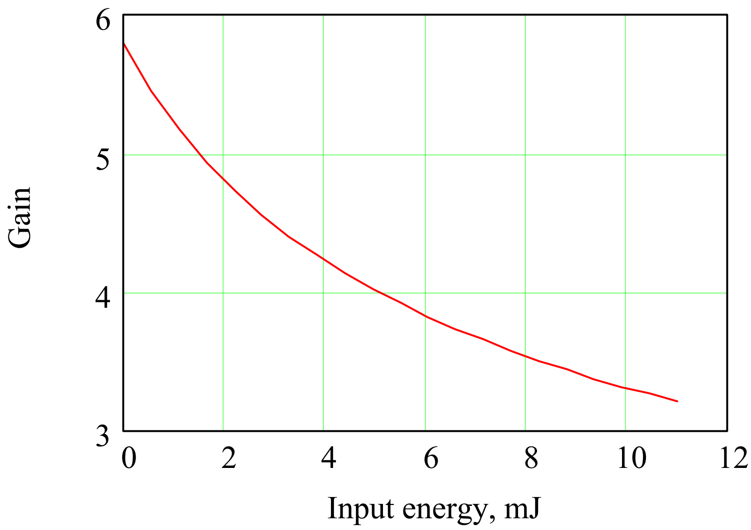


Fig.11.

We had tried to vary parameter α_0 ($0.247 < \alpha_0 < 0.252$) and Γ_s to get minimum of the mean squared deviation (Fig.12).

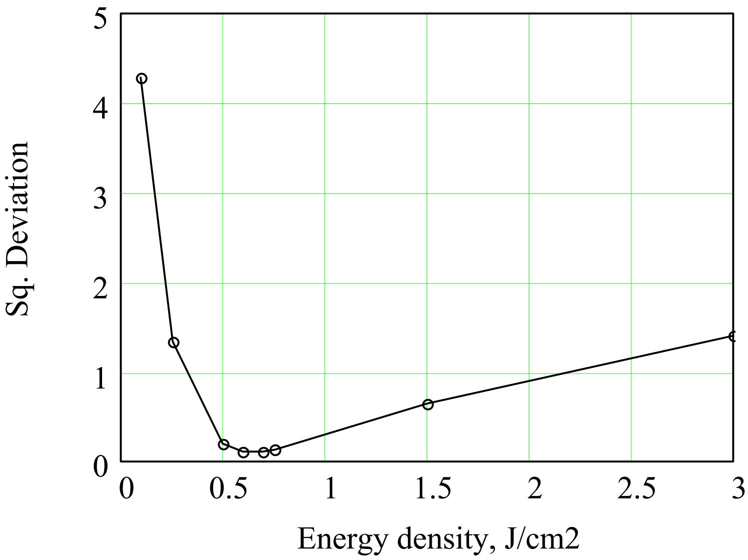


Fig.12.

We get this minimum at the values of parameters:

-the length of the active elements of the amplifier l = 8 cm,

-gaussian beam's radius in front of the amplifier w = 0.1 cm,

-transparency of the "idle" amplifier T_0 = 79.4 %, γ = 0.029 cm^{-1} ,

-initial gain coefficient α_0 = 0.25 cm^{-1},

- energy density of saturation Γ_s = 0.7 J/cm^2 .

The solid lines on Fig.13 and Fig.14 shows as MATHCAD 6 PLUS gives a good approximation of our experimental points except the first two points (nearest to zero) on the Fig.13 at the parameters above. We have two bad experimental points, probably, because of insufficient experimental precision.

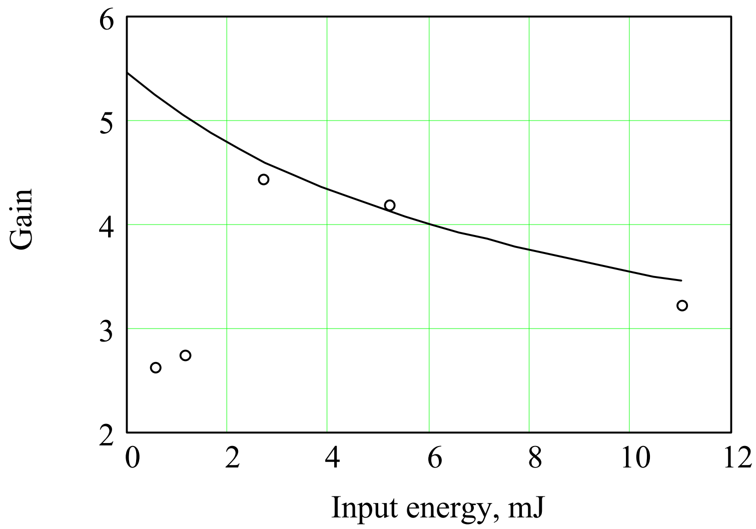


Fig.13.

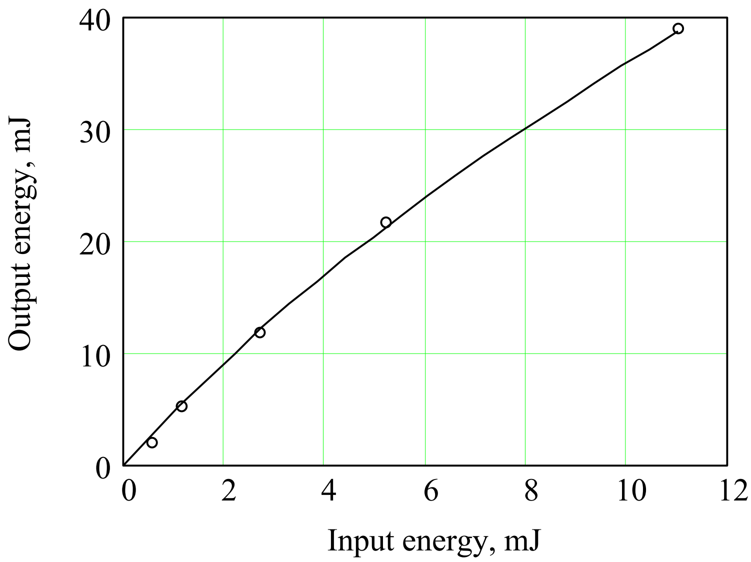


Fig.14.

The effective cross-section of the $^5I_6 - {}^5I_7$ laser transition can be determined through the energy of saturation $E_s = hc / \sigma\lambda$.

(λ=2.92 10^{-4} cm, c=2.998.10^{10} cm/s ,h=6.547.10^{-27} erg.s)

hc=1.96.10^{-16} erg.cm = 1.96.10^{-23} J.cm

(hc/λ)= 6.71.10^{-13} erg = 6.71.10^{-20} J

For E_s = 0.7 J/cm^2 we have σ=9.6 10^{-20} см^2 ,

If we have α_0 = 0.25 cm^{-1} and σ = 9.6 10^{-20} см^2 , it means that initial concentration excited Ho ions on the upper laser level $N_{20} = \alpha_0 / \sigma$ = 2.6.10^{18} cm^{-3} while the total Ho ions concentration is 5.10^{19} cm^{-3} . Therefore ~5% of Ho ions are excited. It seems too small.

We have estimated and measured the main parameters of the active medium for amplifier (it is true for oscillator also) and we have now:

-the length of active medium l= 8 cm,

$\gamma = 0.029\ cm^{-1}$,

$\alpha_0 = 0.25\ cm^{-1}$,

$\Gamma_s = 0.7\ J/cm^2$,

w = 0.1 cm, $S= \pi w^2/2 = 1.57.10^{-2}\ cm^2$,

$E_s = \Gamma_s S$= 11 mJ,

$G_0 \sim (5–7)$.

At these parameters we have estimations:

E_{extr} =28 mJ, then $E_{0ut} = E_{in} + E_{extr}$ =11 mJ + 28 mJ = 40 mJ;

max $E_{avail} = (\alpha_0/\gamma)E_s$ =94 mJ.

First part of our third interim report sanded last year and repeated in this final report is correct. But in second part of them we have found a mistake in determination of the values energy density of saturation $F_s[J/cm^2]$ and initial amplification coefficient $\alpha_0[cm^{-1}]$ .This mistake was caused by

1) small number of experimental points in dependence of the output energy E_{out} on the input energy E_{in} (and hence low precision)

2) determination of the values E_s and α_0 depends on the manner of getting approximation curve (see Fig.1a, Fig.2a and Fig.1b, Fig.2b).

Old data (Fig.15a, Fig.16a): l = 8 cm – the length of the crystal-amplifier; w = 0.1 cm – a gaussian beam radius at the position of the crystal-amplifier; $\gamma = 0.027\ cm^{-1}$ – a losses of the amplifier. We had chosen by “best fitting curves” the values of initial amplification coefficient $\alpha_0 = 0.25\ cm^{-1}$ and energy density of saturation $F_s = 0.7\ J/cm^2$.

New data (Fig.15b, Fig.16b): l = 8 cm – the length of the crystal-amplifier; w = 0.1 cm - gaussian beam radius at the position of the crystal-amplifier; $\gamma = 0.027\ cm^{-1}$ – a losses of the amplifier. We had chosen by “best fitting curves” the values of initial amplification coefficient $\alpha_0 = 0.18\ cm^{-1}$ and energy density of saturation $F_s = 10\ J/cm^2$.

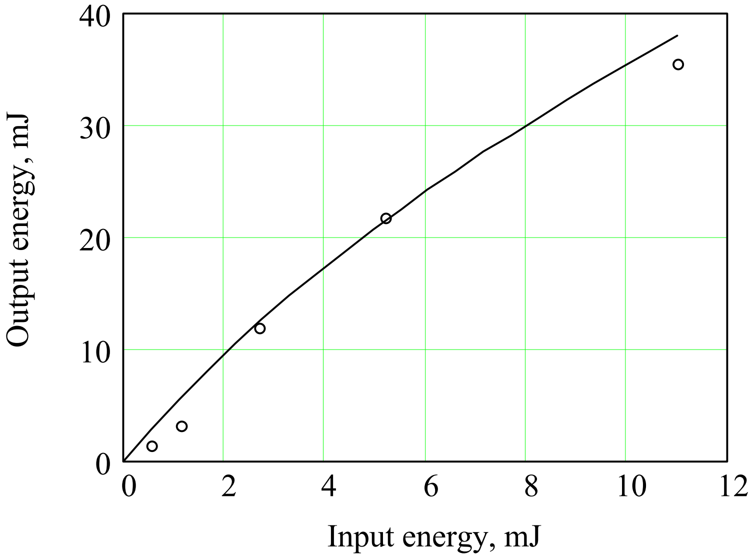


Fig.15a

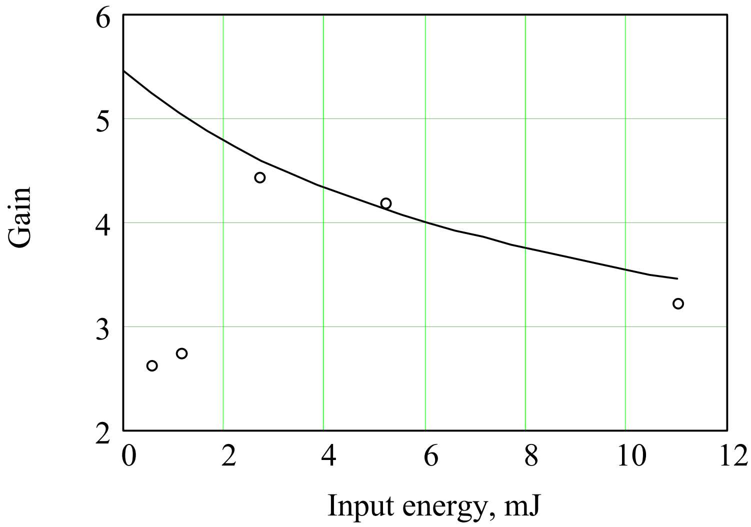


Fig.16a

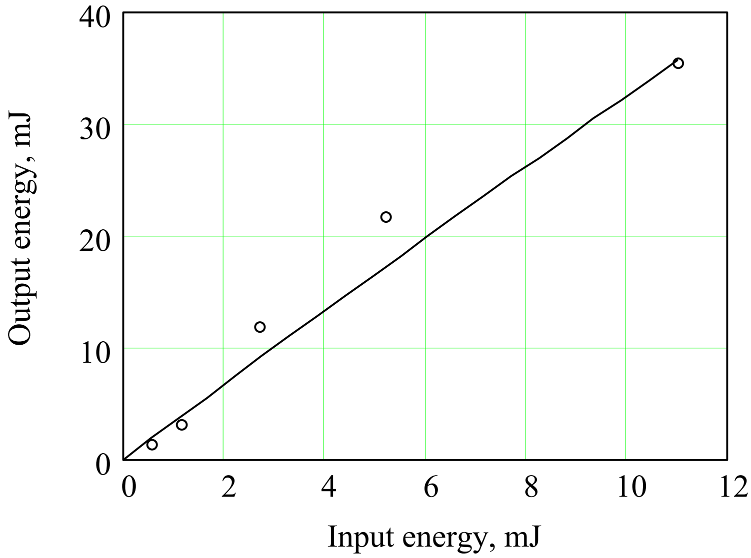


Fig.15b

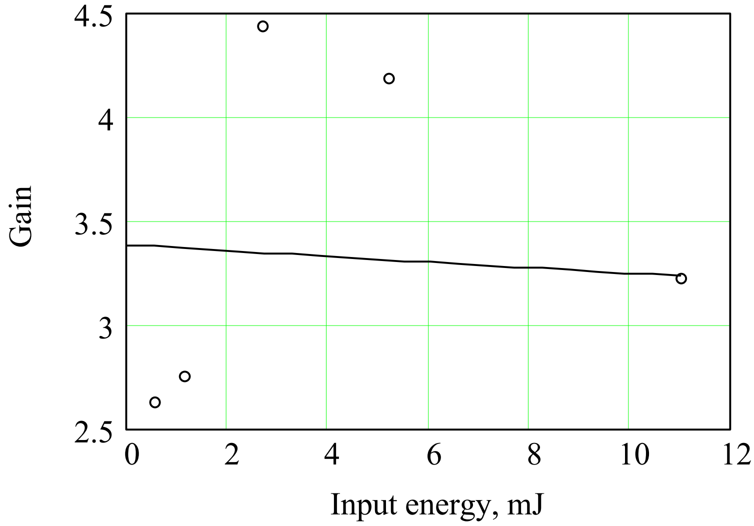


Fig.16b

This figures show that our former accuracy of experimental data insufficient to estimate correctly energy density of saturation F_s and initial amplification coefficient α_0.

We have revised our measurements and increased the number of experimental points until 50 (see Fig.20) instead of 5. It was decreased the pumping pulse duration of the amplifier from 600 μs to 300 μs to make it less then the value of the lifetime of the upper laser energy level (~ 0.5 ms). But it was the reason of decreasing of the pumping energy until 400 J instead of 800 J (at longer pumping pulse duration) to decrease the value of thermal lens. Initial value of the coefficient α_0 was decreased at lower pumping energy and we were must to increase the density of the input energy by means of decreasing of the gaussian beam radius w from 0.1 cm (Fig.18) to 0.04-0.03 cm (Fig.19) with help of the lens f=20 cm (number 7, Fig.17). A confocal parameter of the gaussian beam at the position of the crystal-amplifier is $b = 2\pi w^2/\lambda = 34.6$ cm and the length of the crystal-amplifier is 8 cm.

Our new experimental set-up is shown on the Fig.17.

So we were working with the Q-switched dispersive resonator at λ=2.92 mkm. The length of the resonator was equals to ~ 1 meter, one flat mirror M2 had coefficient of reflection near 100% and output flat mirror M1 had coefficient of reflection 55%; for a Q-switch operation was used electro-optical shutter on the base of $LiNbO_3$ crystal.

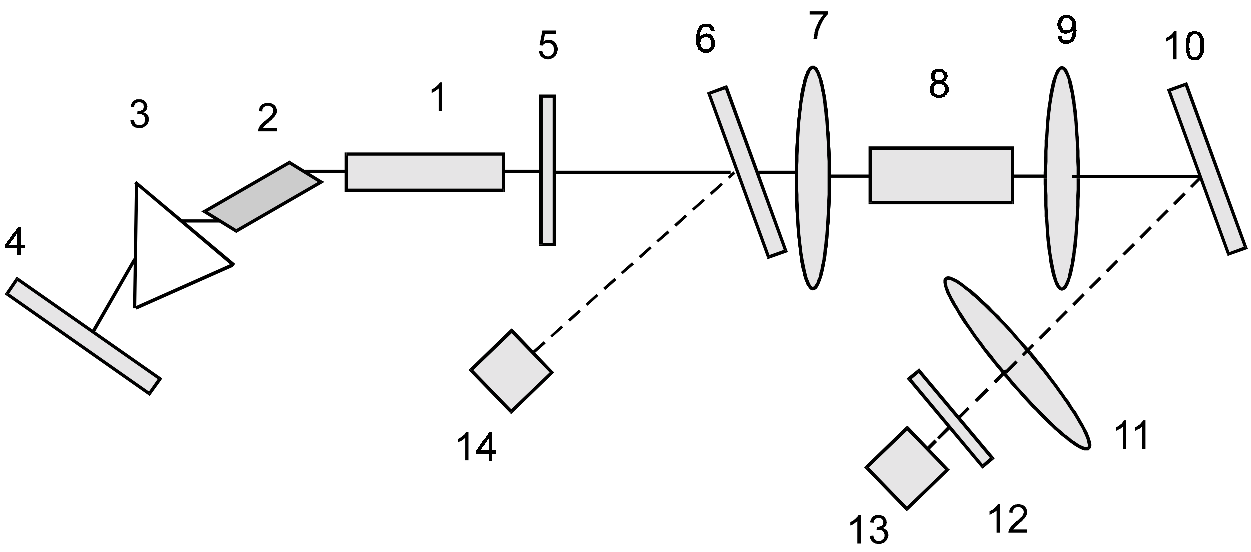


Fig.17.
Experimental setup for measurements of a single-pass gain.

1 - an active element of the master-oscillator; 2 – $LiNbO_3$ Q-switch shutter; 3 – LiF- dispersive prism; 4 – mirror (R=100%, 2.92 μ); 5 – output mirror (R=70%, 2.92 μ); 6 – fused SiO_2 small angle edge; 7 – lens f=20 cm; 8 - active element of the amplifier; 9 – lens f=50 cm; 10 - mirror (R= ~100%, 2.92 μ); 11 – lens f=50 cm; 12 – scatterer; 13 – photo detector U_2 ; 14 – photo-detector U_1.

It should be mentioned that using now small angle edge "6" and mirror (R= ~100%, 2.92 μm) "10" instead of fused SiO_2 plane-parallel plates before allow us get rid off interference bands on the photo-detectors and sufficient instability of measuring signals.

The output energy of the master-oscillator in Q-switch TEM_{00} -mode at λ=2.92 mkm is about 10-15 mJ with pulse duration ~150 ns and the gaussian beam radius w~1 mm at the position of the lens 7 installed in front of Ho-amplifier on the crystal with 5 mm in diameter and illuminated length equals to 80 mm.

The gaussian beam transversal distribution was measured with help a narrow slit (less then 0.1 mm) and two photo detectors, one of them (supporting) in front of the slit and another one (signal) behind the slit. The slit was placed at the distance equals to 30 cm from the flat output mirror of the Ho master-oscillator. We have moved the slit across the Ho laser beam and measured signals of both photo detectors. The ratio of two signals gives a function of distribution which we search and which is shown on the Fig.18. We would like to note that the spots of the Ho laser beam on the developed black film have round shape.

We have got an approximation curve to fit our experimental points (solid line on the Fig.18). The right wing of the distribution is distorted but the main part of this distribution very similar to TEM_{00} mode with the beam radius equals to 0.1 cm.

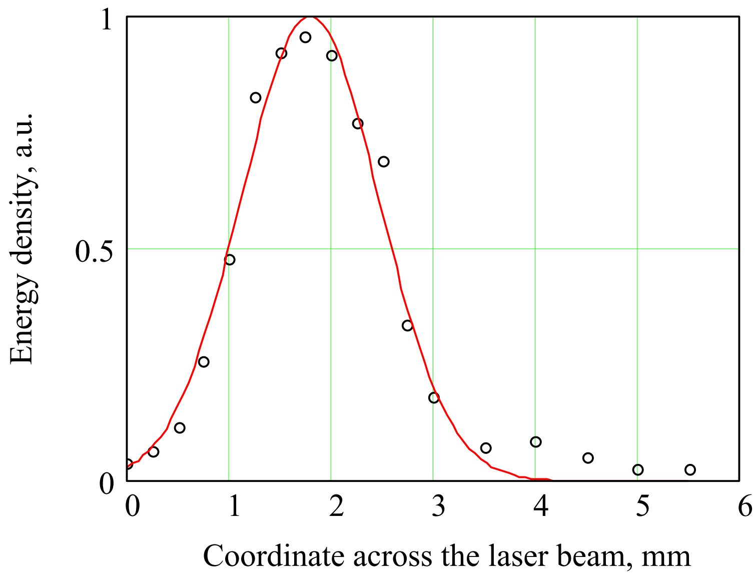


Fig.18.

We have measured also spot size diameter of the laser beam after the lens 7 to determine an energy density injected into amplifier. Next figure shows dependence of diaphragm transmission on its diameter. Solid line gives transmission of gaussian beam with radius w:

$$T(r,w) = 1 - \exp(-2 \cdot \left(\frac{r}{w}\right)^2),$$

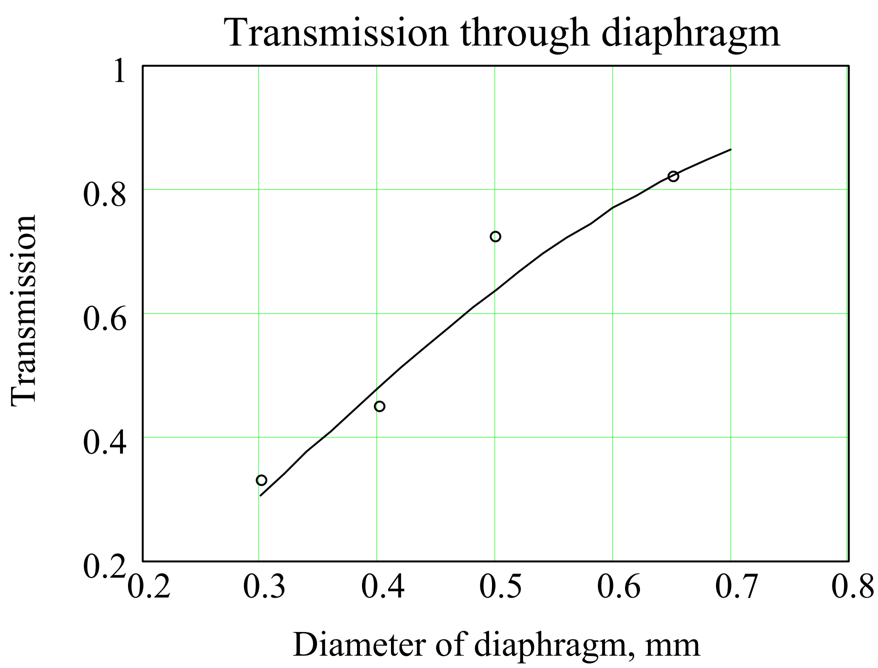


Fig.19.

So we have a radius of gaussian beam in front of our amplifier w=0.35-0.4 mm.

The next step was to measure output energy of amplifier E_{out} with dependence on input energy E_{in} and to determine parameters of our amplifier mentioned above. On the Fig.20 is shown dependence E_{out} on E_{in} at pump energy 400 J (C=200 mkF, U=2 kV).

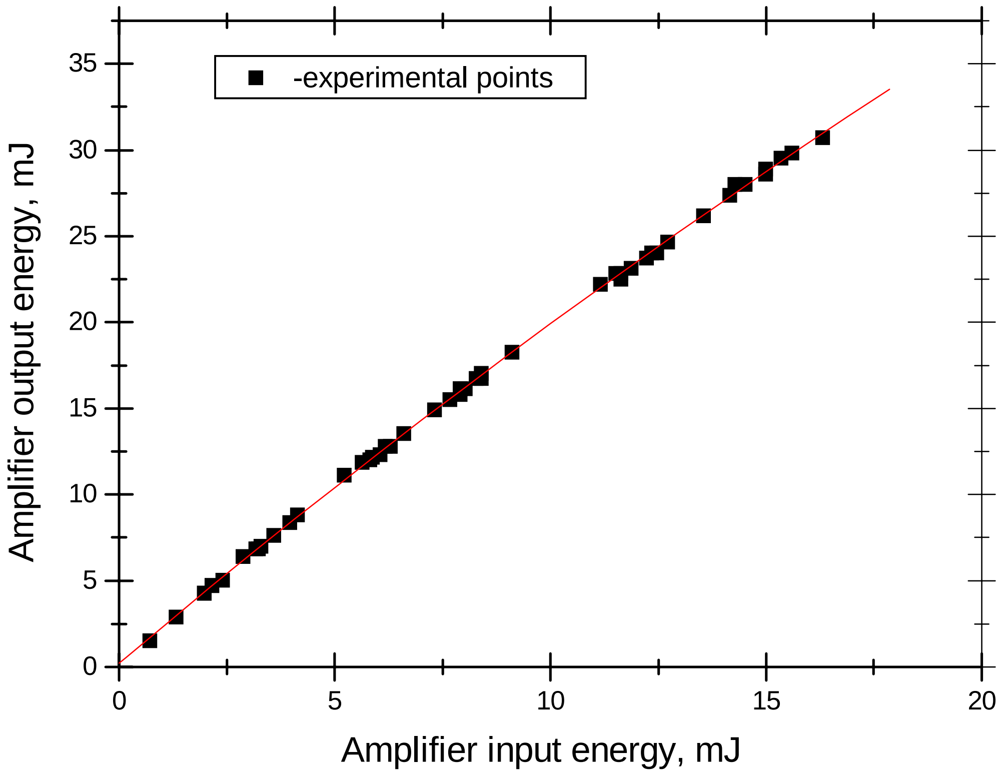


Fig.20.

Polynomial Regression on Fig.20.
Y = A + B1*X + B2*X^2

Parameter	Value	Error
A	2,26282E-4	9,04661E-5
B1	2,10021	0,02402
B2	-13,21232	1,35387

R-Square (COD)	SD	N	P
0,99962	1,66819E-4	50	<0.0001

where coefficient B1 corresponds to unsaturated gain factor G_0 at the weak input signal 1 mJ< E_{in} <5 mJ. So we have from Fig.20 the value $G_0 = 2.1$.

We solved this equation (*) numerically using experimental data (Fig.20(6)) and method of least squares with help of mathematical package MATHCAD 6 Plus, taking into account transversal energy distribution of the laser beam.

Fig.21shows as Sq.deviation depends on energy density of saturation.

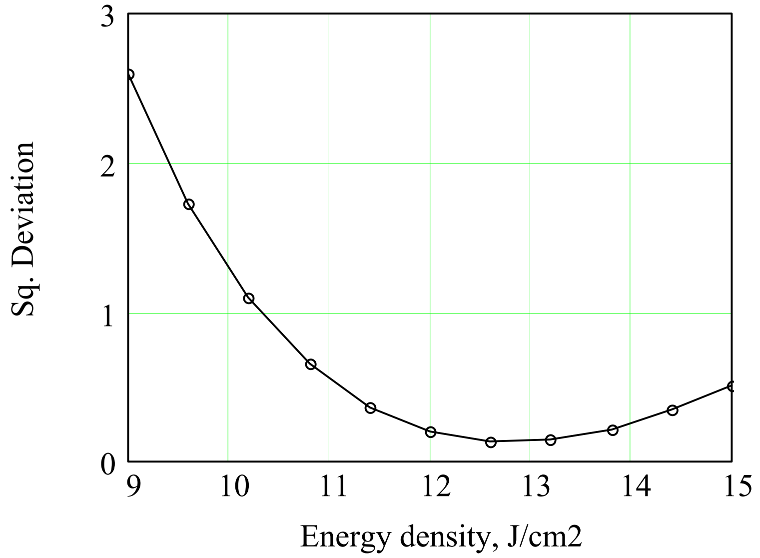


Fig.21.

We get the minimum of Sq.deviation at the values of parameters:

-the length of the active elements of the amplifier l = 8 cm,

-gaussian beam's radius in front of the amplifier w = 0.04 cm,

-transparency of the "idle" amplifier T_0 = 80.4 %, γ = 0.027 cm^{-1} ,

-initial gain coefficient α_0 = 0.126 cm^{-1} ,

- energy density of saturation Γ_s = 12.6 J/cm^2 .

We have got fit-function (solid line), which is shown on Fig.21. This function approximate our experimental points rather good at values of parameters α_0 = 0.126 cm^{-1} - initial gain coefficient, γ = 0.027 cm^{-1} - non-resonant passive losses, Γ_s = 12.6 J/cm^2.

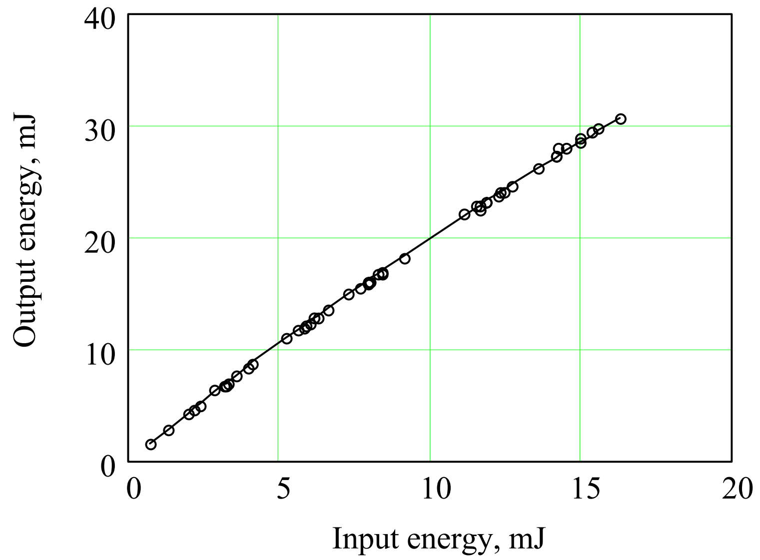


Fig.22.

The spot size of the gaussian beam is $S=\pi w^2/2=2.51x10^{-3}$ cm^2 at w=0.04 cm ,
then $(E/S)/F_s$ = (15 mJ/2.51×10^{-3} cm^2)/12.6 J/cm^2 =5.97 J/cm^2 /12.6 J/cm^2 = 0.47 ,
where F_s is the energy density of saturation. We see that the input energy E ~ 15 mJ at the gaussian beam radius w=0.04 cm gives the input energy density E/S less then 50% of F_s, and dependence of the output energy on the input energy almost linear.

Fitting curve (solid line) for a gain factor G (Fig.23) at the same parameters α_0 = 0.126 cm^{-1}, γ = 0.027 cm^{-1}, Γ_s = 12.6 cm^{-1} approximate experimental points not so bad except interval of the input energy from 0 to 5 mJ, where precision of the experimental data not so good and the value of G_0 has rather large experimental error.

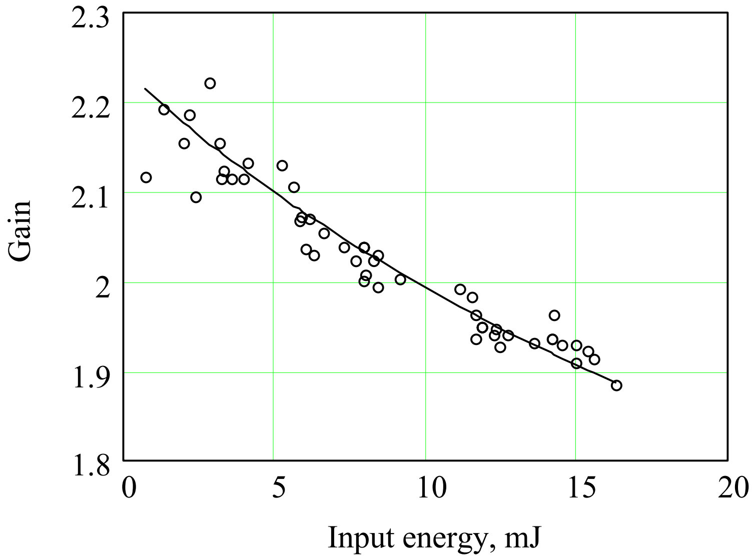


Fig.23.

The effective cross-section of the $^5I_6 - {}^5I_7$ laser transition can be determined through the energy of saturation $E_s = hc/\sigma_{eff}\lambda$, (λ=2.92 10^{-4} cm, c=2.998.10^{10} cm/s ,h=6.547.10^{-27} erg.s, hc=1.96.10^{-16} erg.cm = 1.96.10^{-23} J.cm, hc/λ= 6.71.10^{-13} erg = 6.71.10^{-20} J) and if Γ_s =12.6 J/cm^2, then σ_{eff}=5.3.10^{-21} cm^2. If we have α_0 = 0.126 cm^{-1} and σ = 5.3.10^{-21} cm^2 , it means that initial concentration excited Ho ions on the upper laser level $N_{20} = \alpha_0/\sigma$ = 2.3.10^{19} cm^{-3} while the total Ho ions concentration is 5.10^{19} cm^{-3} . Therefore ~ 46% Ho ions are excited. We can use just one half of them as maximum because of self-limited transition, that corresponds to ~(hc/λ)(N_{20}/2) = 6.71.10^{-20} J×1.10^{19} cm^{-3} = 0.67 J/cm^3 . A volume of the TEM_{00} mode inside of the crystal-amplifier is about l×S= l×$\pi w^2/2$ = 8 cm×2.51.10^{-3} cm^2 = 2.10^{-2}cm^3, and then extracted output energy from amplifier E_{extr} equals to 13.5 mJ.

We note in conclusion that Ho master-oscillator and amplifier are working properly and gives Q- switched giant pulses in TEM_{00} mode with the beam radius w=0.1 cm, the pulse energy E_{out} almost 60 mJ and pulse duration ~150 ns.

We have estimated and measured the parameters of the active medium for amplifier (it is true for oscillator also) at pumping energy 400 J, TEM_{00} mode with the beam radius w=0.04 cm and we have now:

the length of active medium L= 8 cm,

$\gamma = 0.027\ cm^{-1}$,

$\alpha_0 = 0.126\ cm^{-1}$, $S= \pi w^2/2 = 2.51.10^{-3}\ cm^2$,

$\Gamma_s = 12.6\ J/cm^2$ – (this value is just estimation and can be in range 10 – 15 J/cm^2, precision of the experimental data is not high enough),

w = 0.04 cm, $S= \pi w^2/2 = 2.51.10^{-3}\ cm^2$,

$E_s = \Gamma_s S$= 31.6 mJ,

$G_0 \sim 2.25$.

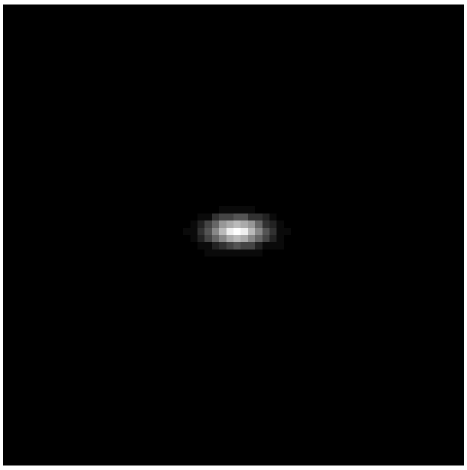
At this parameters we have estimations for $E_{extr} = E_{out} – E_{in}$ = 30mJ – 16mJ = 14 mJ (very close to upper estimation) and for max $E_{avail} = ((\alpha_0-\gamma)/\gamma)E_s$ ~115 mJ , but for that we need to have $E_{in} \sim E_s = \Gamma_s S$= 31.6 mJ. Now we have E_{in} twice less and we need to increase output energy of master-oscillator to get E_{avail} ~100 mJ.

We will try as next step to increase output energy of master-oscillator until 30 mJ to get E_{avail} closer to 100 mJ and to increase sufficiently the precision of determination energy density of saturation.

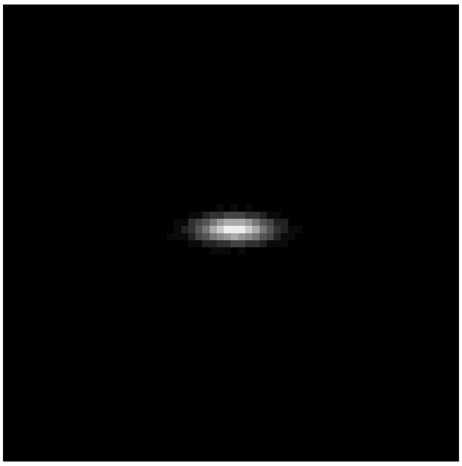
Task 4. To study experimentally the possibility to get OPO conversion efficiency close to 20%.

Unfortunately we couldn't fulfill the task 4 – the main part of our work (resonant OPO on GaSe crystal). A large birefringence, Fresnel losses, softness and flexibility makes this nonlinear material more difficult then we thought. We made many attempts to get OPO oscillation but without success. Long time we couldn't realize the reason of that. At last we have made a numerical experiment with help of commercial program package "Fresnel" originated and developed by Rene V.Serov with collaborators (GPI). This numerical experiment was concerned to estimate astigmatism in OPO resonator with two GaSe crystals oriented to resonator axis at 55 degrees opposite each other (as on Fig.3). We have got not much time to use R.V.Serov's computer free(!) and have calculated just pump frequency gaussian beam transformation in shape (transversal distribution) after 30 round trips inside OPO resonator. We have realized at last that proposed scheme of OPO resonator with two GaSe crystals inside has

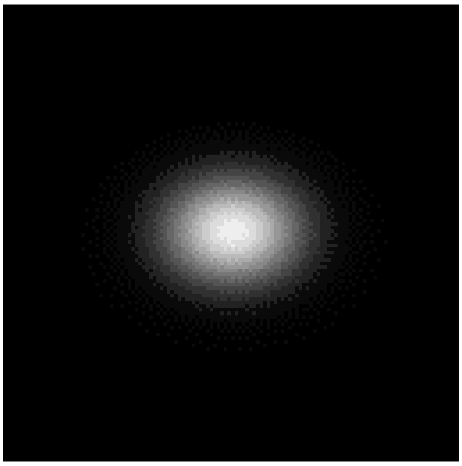
very large astigmatism. Last circumstance was for us big and bad surprise. Lower are shown 5 patterns of transversal distribution for pump wave at 5 different distances from OPO mirrors separated each other to 100 mm. Under each pattern shown distance in mm from one mirror and (in brackets) from another mirror.



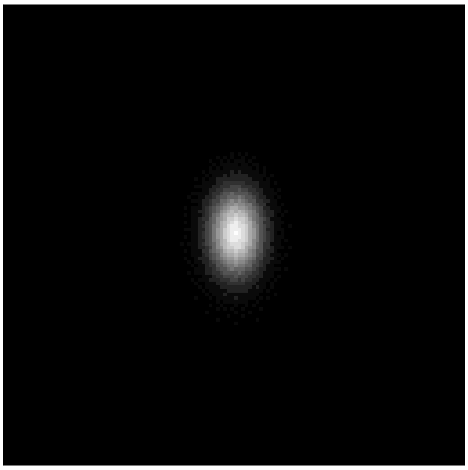
60 (40)



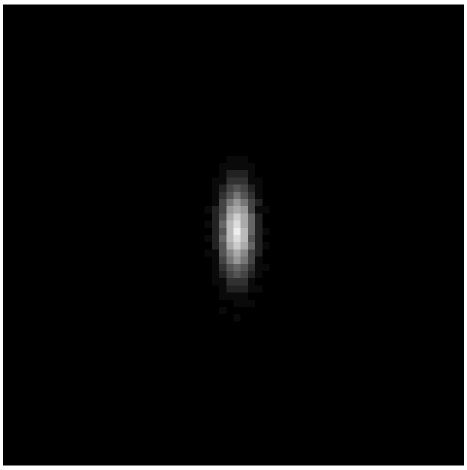
70 (30)



80 (20)



85 (15)



90 (10)

Third and fourth patterns show big difference in laser spot shapes separated just on 5 mm (just half of thickness of GaSe crystal). It means that overlapping of interacting parametric waves would be bad enough and interacting length would be much less then GaSe crystal thickness. Thus all our estimations of threshold pump power mentioned above are not valid for proposed scheme of OPO resonator.

It should be noted that detail calculation of spatial distributions of three interacting waves in OPO resonator was impossible to us because of much time of calculation and commercial character of this very powerful "Fresnel" program package which costs $2000 and should be bought to use it permanently.

A paper about Ho-amplification will be published in the Russian journal "Laser Physics" this year with acknowledgements to EOARD foundation.

References

1.Morris P.J.,Luthy W.,Weber H.P.,Rusanov S.Ya.,Zagumennyi A.I.,Shcherbakov A.I., Umyskov A.F. J.Quant.Spectrosc.Radiat.Transfer, **52**, 545 (1994).

2.A.Siegmen "Lasers" , N.Y.

3.O.Svelto "Principles of Lasers", Plenum Press, N.Y., London.

Principal investigator Lev A.Kulevsky

31 May 2001